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A Model Describing Filter Removal Efficiency at Different Inlet Concentrations

Chi-Wen Kuo*[1], Tzu-Sou Chuang[2], Luh-Maan Chang[3]

Department of Civil Engineering, National Taiwan University, Taipei, Taiwan.

[1]d98521023@ntu.edu.tw; [3]luhchang@ntu.edu.tw

Abstract

The goal of this study is to model the behavior of removal efficiency from the filtration experiments of former research. Filters have been used widely for industrial manufacturing and personnel air conditioning to protect from airborne molecular contaminations (AMC). Extensive testing has been performed in order to get a clear picture of filtration mechanisms. However, only few researches have been done to find critical parameters regarding to the filter removal efficiency at different concentration. This paper presents a mathematical model based on former researches of the Wheeler-Jonas equation, with a numerical technique of finite element method (FEM) for finding the filter removal efficiency. Hence, the proposed model divided the whole filtration domain into simpler and smaller parts to extrapolate experiment which results in different inlet concentration situations making it promising for filter efficiency prediction and can further help to optimize the design and maintenance of the air filtration systems.

Keywords

Removal Efficiency; Filter; Concentration; Efficiency Model; Wheeler-Jonas Equation

Introduction

To achieve an AMC free environment in buildings and factory plants, filters are widely used to adsorb unacceptable substances[1][2][3]. The Wheeler-Jonas equation is a well-known simulation equation for describing organic vapor breakthrough times of activated carbon filters and the applicability of the equation has been proven in former researches[4][5][6].

Wheeler-Jonas equation:

$$t_b = \frac{W_e W}{Q c_{in}} - \frac{W_e \rho_b}{k_v C_{in}} \ln\left(\frac{C_{in} - C_{out}}{C_{out}}\right) \quad (1)$$

t_b = breakthrough time (min)

W = weight of the carbon (gcarbon)

W_e = static adsorption capacity of the activated carbon (g/gcarbon)

C_{in} = filter inlet concentration (g/cm3)

Q = volumetric flow rate (cm3 /min)

ρ_b = bulk density of the carbon bed (gcarbon/cm3)

k_v = overall adsorption rate coefficient (min-1)

C_{out} = chosen breakthrough concentration(g/cm3)

Previous studies of empirical and semi-empirical breakthrough models have shown that the adsorption rate constant in the Wheeler-Jonas equation is insignificant on inlet contamination concentrations [7][8]. This leads to a concept of constant diffusivity (diffusion coefficient) under identical kinetic temperature terms and physical conditions. Constant diffusivity establishes the foundation of mathematical calculation to link the filter breakthrough times with inlet and breakthrough concentration. Therefore, the Wheeler-Jonas equation is simplified and all the parameters are reduced, basically depending on the characteristics of the filter material and the AMC concentration. When the physical conditions of less influences have been taken into consideration, Wheeler-Jonas

equation could be rewritten as a function of y in k_v 、C_in and C_out[9]. Filter removal efficiency can be translated by an equation with three variables F(k_v,C_in , C_out).

Fick's First Law of Diffusion is applied to calculate the VOC mass transfer, which can be expressed in one-dimension (1-D) as:

$$J = -r\frac{d\emptyset}{dx} \quad (2)$$

Where

J is diffusion flux [(amount of substance) per unit area per unit time]

r is diff usivity (diffusion coefficient)

Ø is the concentration of VOC

which assumes that the mass of diffusion from the high-concentration zone to the low-concentration zone is directly proportional to the diffusivity and the concentration gradient.

Experimental Procedure

This model makes three assumptions. First, the filter in the air filtration process is not saturated and the pollutants that have entered into the filter will not be released again. Second, the pollutant concentration at the filtration interface is extremely small during the continuous absorption. Third, the filtration procedure is broken down to limited stages with nearly the same conditions and thus the same diffusivity.

At the first step of the method is to divide the domain of the whole filtration system into a collection of identical elements, with each element represented an individual filter. Be different from the previous studies of empirical and semi-empirical equations, filtration process is redefined by a set of filter elements .

To explain the approximation removal efficiency of the whole process, FEM is introduced to construct an integral of the inner elements of the filtration system. In other words, it is a mathematical procedure to integrate a set of ordinary differential equation from finite segments of the filtration system.

Serial experiments were performed to verify the relationship between the inlet concentration and removal efficiency. Firstly, the overall filtration was divided into 500 cycles of diffusion and absorption. The removal efficiency in the experiment under a certain inlet gaseous chemical concentration circumstance was used as the basis to calculate mass transfer coefficient. The calculated consequences of the efficiency model are close to the controlled experiments, especially when the inlet chemical concentration is above the range of 100 ppb.

Results and Discussion

From the derived formula, the removal efficiency of a given air filtration system upon changing inlet concentration can be predicted if certain inlet pollutant concentration is known. The actual removal efficiency data are known as a boundary condition. The efficiency simulation diagram is shown as figure 1.

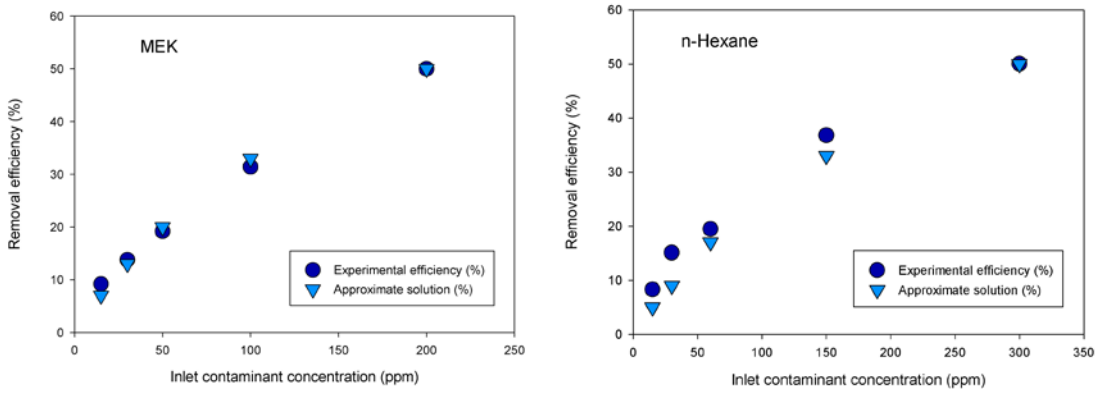

FIG. 1 REMOVAL EFFICIENCY SIMULATION DIAGRAM FOR DIFFERENT CONCENTRATIONS MEK AND N-HEXANE

By comparing the experimental data with the predicted values illustrated, it is noted that the data set in the experiment show good consistency between the experiments and predictions. Multivariate correlation coefficients are widely used in statistical analysis in order to compare two series of data for the purposes of model recognition and disparity measurement. A correlation matrix is used to summarize the strength of the linear relationships between each pair of variables calculated using the Pairwise Method, which performs correlations for all rows of each pair of columns with non-missing values. Multivariate analysis was performed, utilizing confidence intervals of correlation to show whether the hypothesis was true, and measuring the sampling distribution. The visual result of multivariate correlation analysis is shown in figure 2.

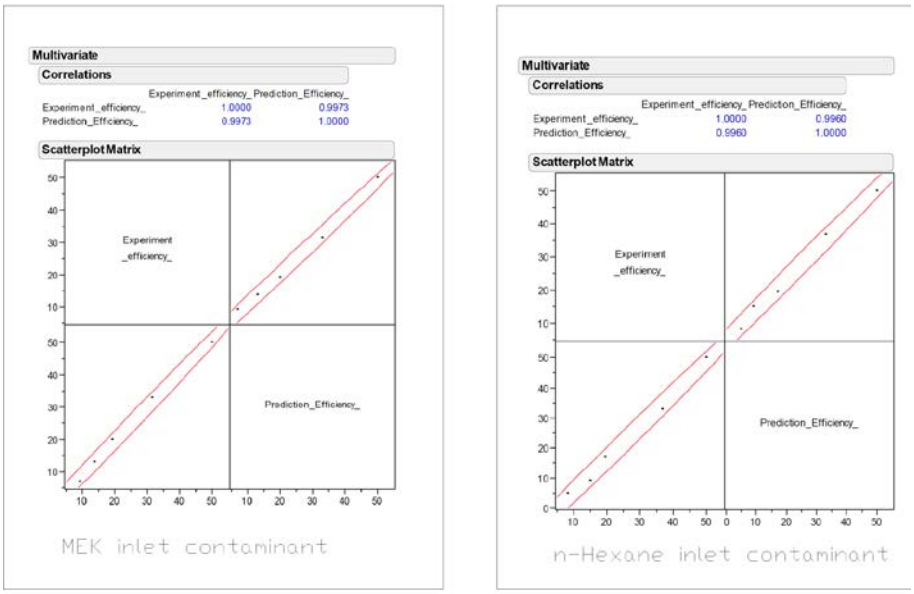

FIG. 2 SAS JMP MULTIVARIATE CORRELATION INDEX ANALYSIS OF REMOVAL EFFICIENCY PREDICTION CURVE VERSUS EXPERIMENT RESULTS OF MEK AND N-HEXANE INLET CONTAMINANTS [10]

Conclusions

In this study, the proposed efficiency predicting model bridges the gap between mathematics and empirical methods in the topology map of filter efficiency estimation. An important insight into pollutant mass transfer behavior was gained based on the concept of treating filtration process as the combinations of small transferring steps and by using the integration technique to instantly simulate the removal efficiency in various inlet concentration situations. Once an operational air filtration module removal efficiency is known, the efficiency prediction model can be used to optimize the design and maintenance of air filtration systems. The applicability of this method could be further enhanced to be integrated for complex hybrid filtration systems.

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